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On Missing Nails and Distant Butterflies:
Clausewitzian Friction in Models of Combat

Dr. Charles McLane, Ms. Teresa Wilson, June 2007

Our Poster Child: A Pathological Example

- **Constructive simulation using VV&A'd model**
  - **year 2020 scenario**
  - **mix of advanced and legacy aircraft**
  - **supporting expeditionary ground force**
- **Objective: quantify operational benefits of**
  - **Network Centric Operations (NCO)**
  - **Non-Traditional Intelligence, Surveillance, and Reconnaissance (NTISR)**

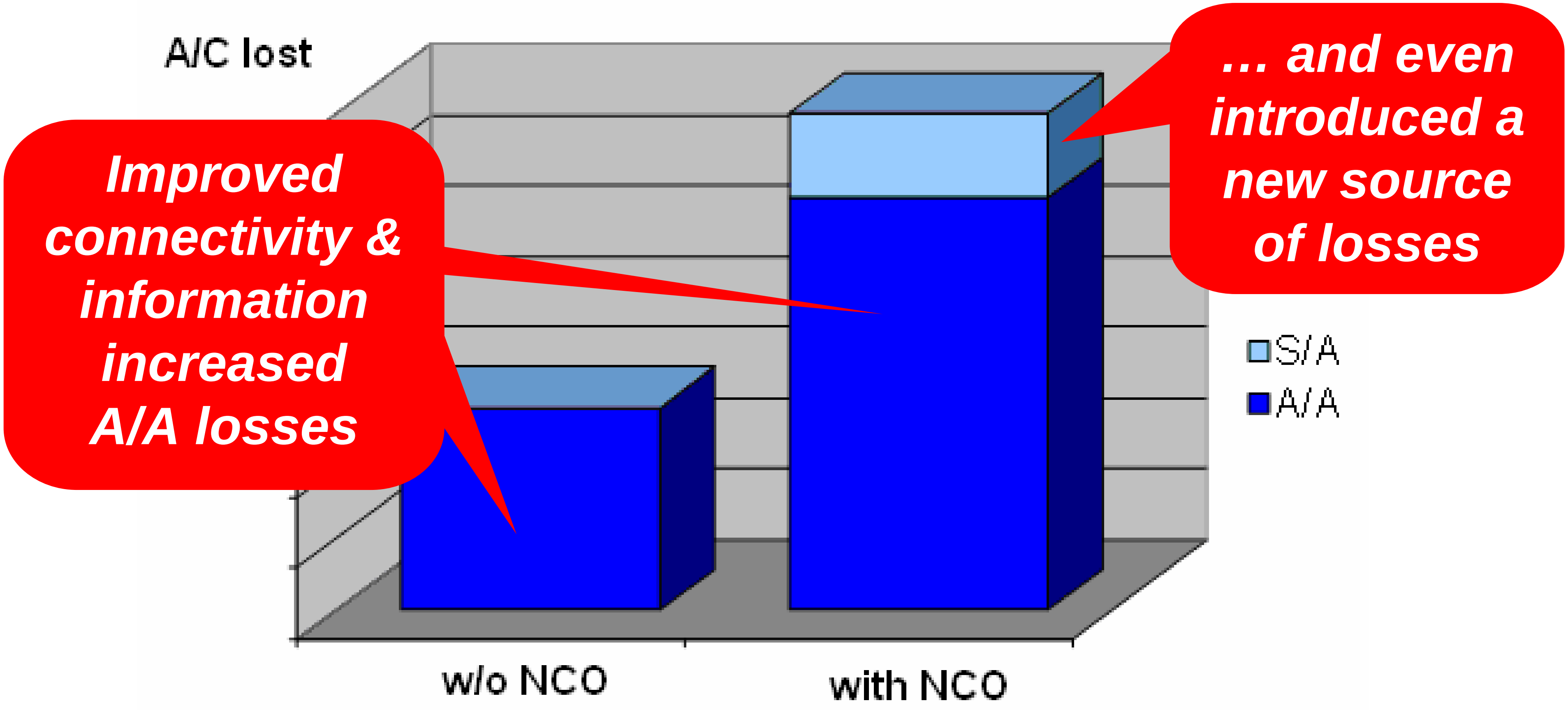
This OA study lead to a clear anomaly

NCO/NTISR improved a number of MOPs without a single downside.

- **Reduced multiple communication latencies**
- **Reduced multiple decision latencies**
- **Increased sensor information**

Yet model results showed a worse MOM…

MOM: Number of Blue Aircraft Lost



What's going on?

Something Subtle Happened

The attentive child at Mother’s knee in the mid 1300s could tell us.

Chaos entered the picture

Expressions of Chaos

- **"For want of a nail …"**
  English nursery rhyme, c 1360**.**
- **"The fog and friction of war"**
  Carl von Clausewitz, 1806
- **"A butterfly in Tokyo … tornado in Topeka"**
  chaos cliché, c 1975
- **"Non-monotonicities"**
  Andreas Tolk, c 1990
- Rand/MORSS Paper: **Non-Monotonicity, Chaos, and Combat Models**
  J. A. Dewar, et al., 1990

Chaos comes under many names.

Chaos Label Varies by Discipline

- **System analysis – “unstable dynamic system”**
- **Statistics – “non strongly causal”**
- **Our label – “chaotic”**
  (extreme sensitivity to initial conditions)

Problems lurk in our models’ woodwork.

One Genius' Take …

"A critical, if somewhat hidden, assumption is that given only an *approximate* rather than an exact knowledge of a system's initial conditions, one can still calculate at least the system's *approximate* behavior."

Richard Feynman

This applies to military OA – read "initial conditions" as scenario, threat laydown, …

The more realistic our models, the more possibility that chaotic outcomes will occlude insight.

Chaotic instabilities can occur in both deterministic and stochastic models.

There are Means to Treat Chaos

- Replications with identical input helps resolve Monte Carlo noise but doesn’t resolve sensitivity to initial conditions

- Sampling the problem (input) space can help resolve chaotic-system noise – for some chaotic systems, the full response ensemble can be depicted

Developing solutions requires a clear understanding of the problem source.

A Few Sources of Chaotic Effects

A combat model is a response function, F, mapping system MOPs, CONOPS, and scenarios into outcomes.

Results = F(MOPs, CONOPS, scenario)

Each argument and F( ) itself holds chaotic risk:

- **Feedback, or chance, in F( )**
- **Threshold sensitivities to MOPs or scenario**
- **Non-optimal CONOPS by Red or Blue**

How can we deal with chaotic systems?

"Think deeply of simple things."

Arnold Ross

We begin our probe with a simple problem.

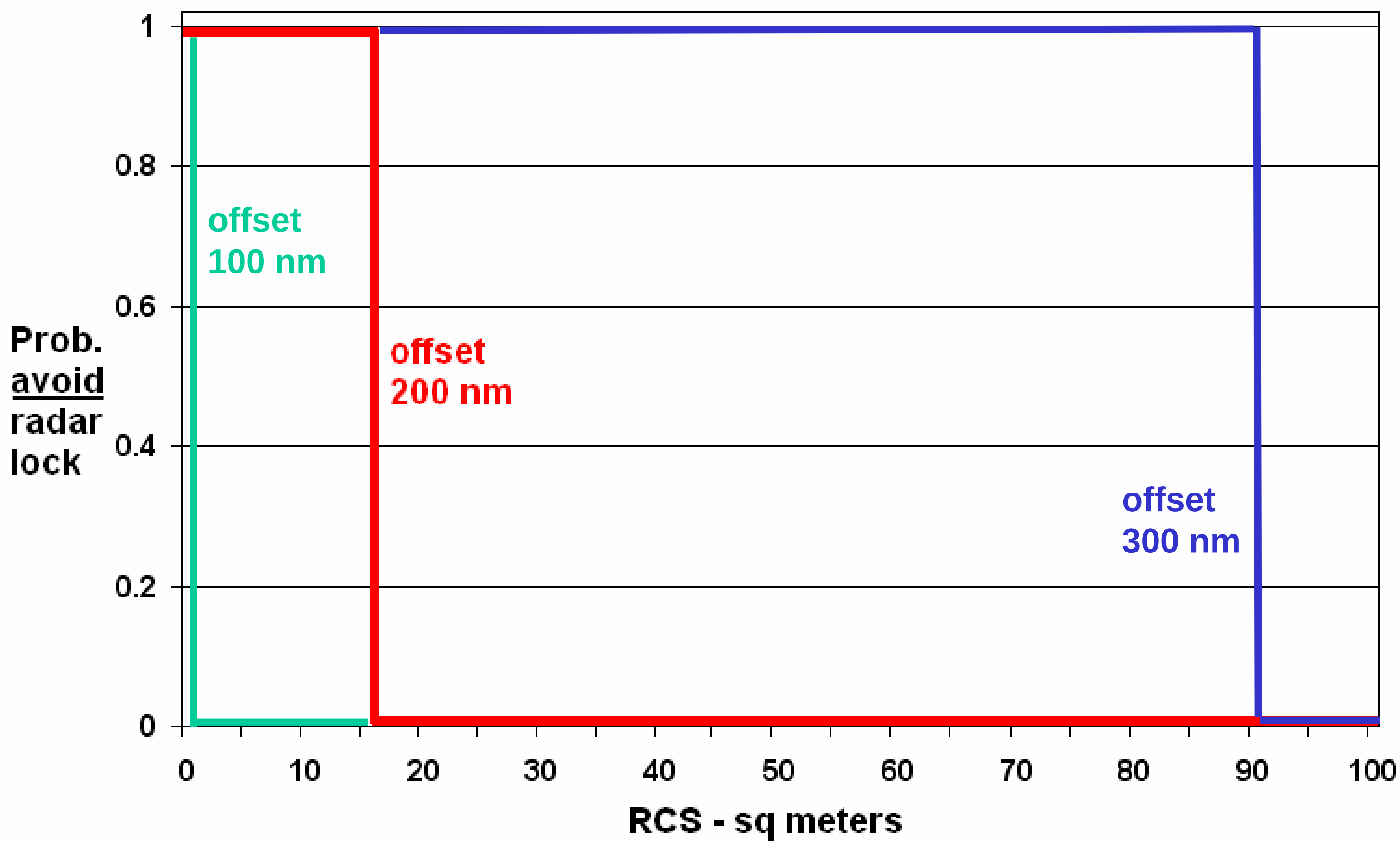
A Simple Problem

Sensitivity of Radar-lock to RCS:

- **Spherical signature**
- **Cookie-cutter $\sqrt[4]{RCS}$ range**
- **Sensitivity: 100 nm vs. 1 m^2 RCS**

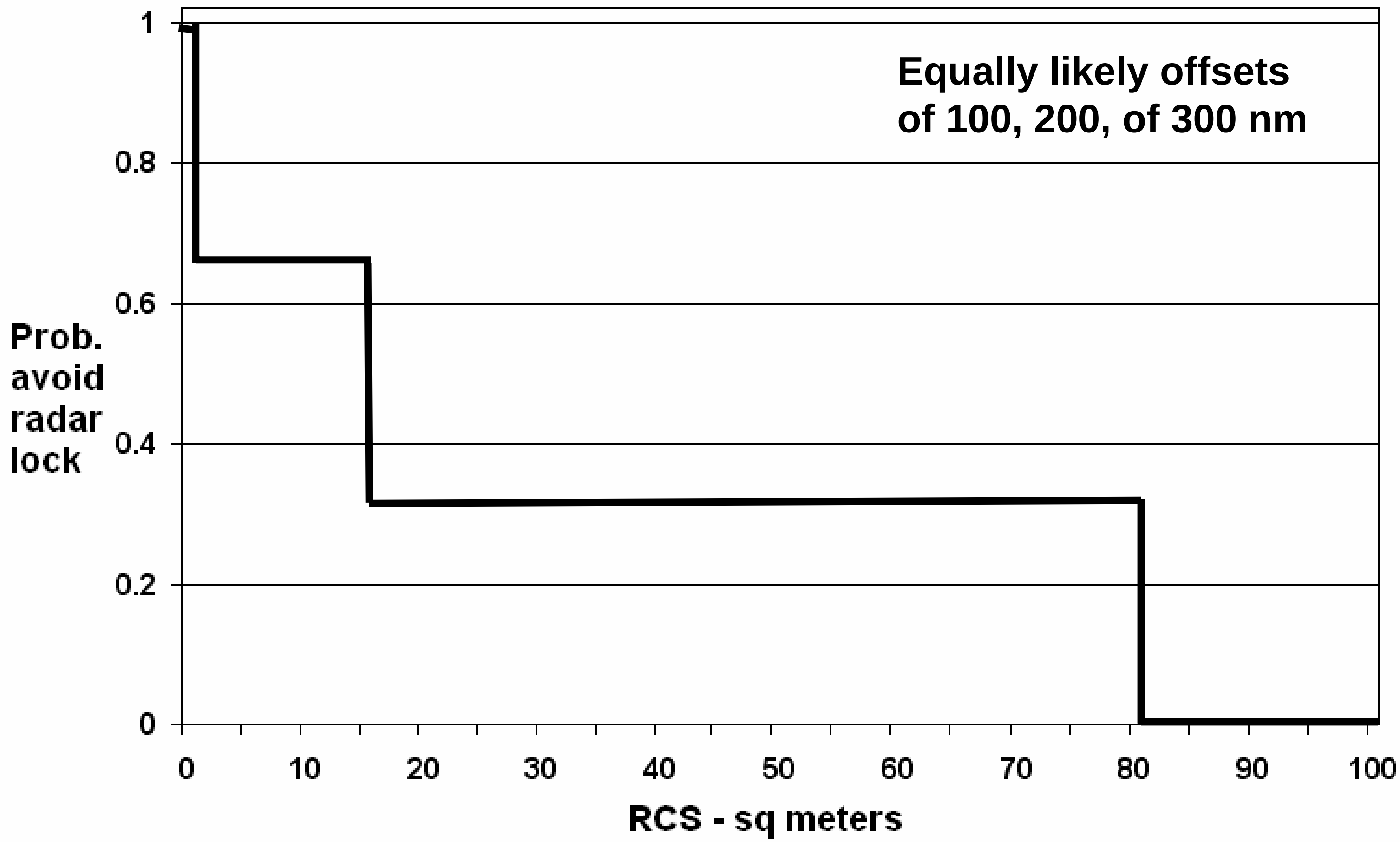
The sensitivity depends on our scenario

RCS Impact Depends on Threat Offset



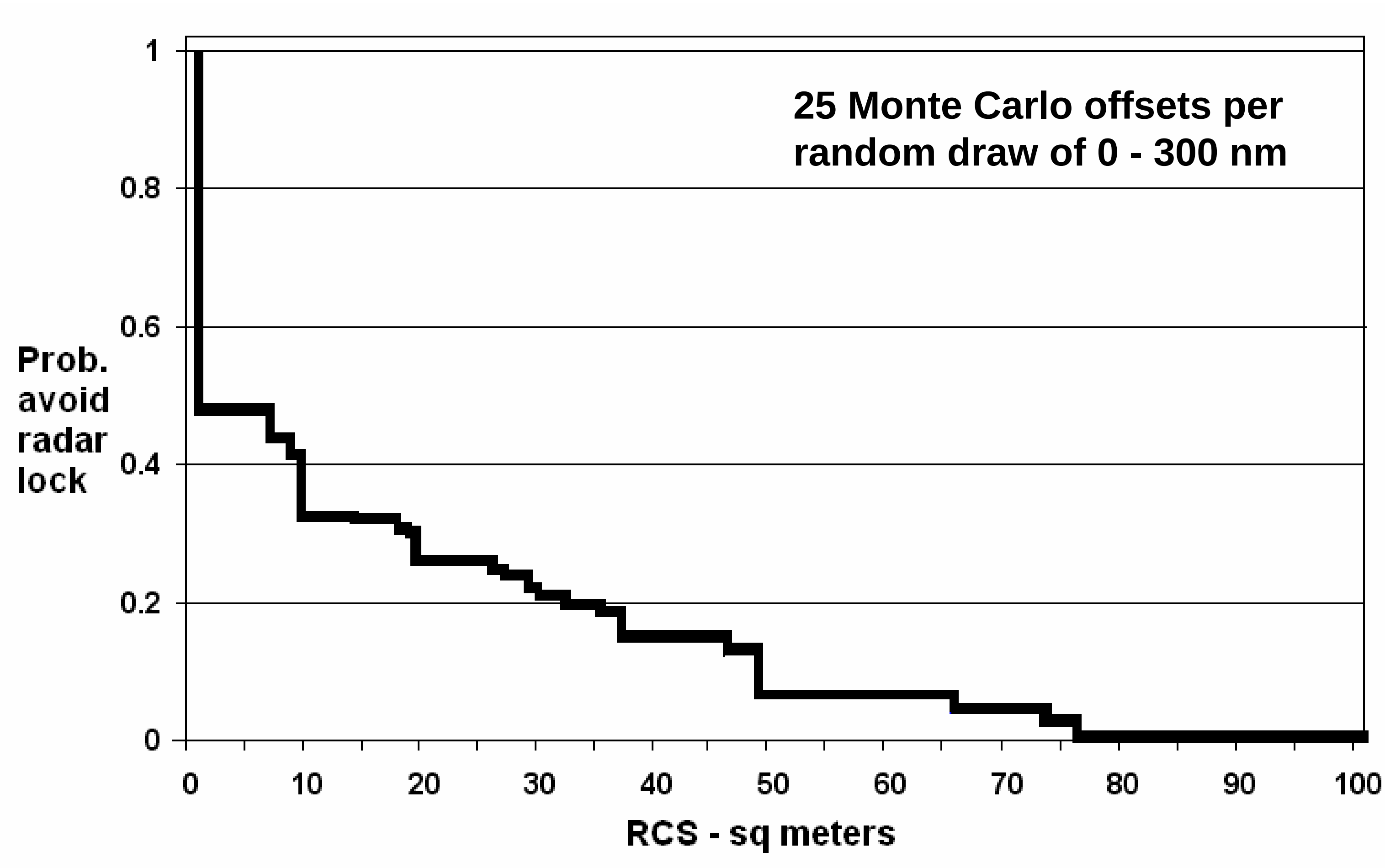
We can hedge our bet as to which offset.

Equally-Weighted Results for an Ensemble of Three Offsets



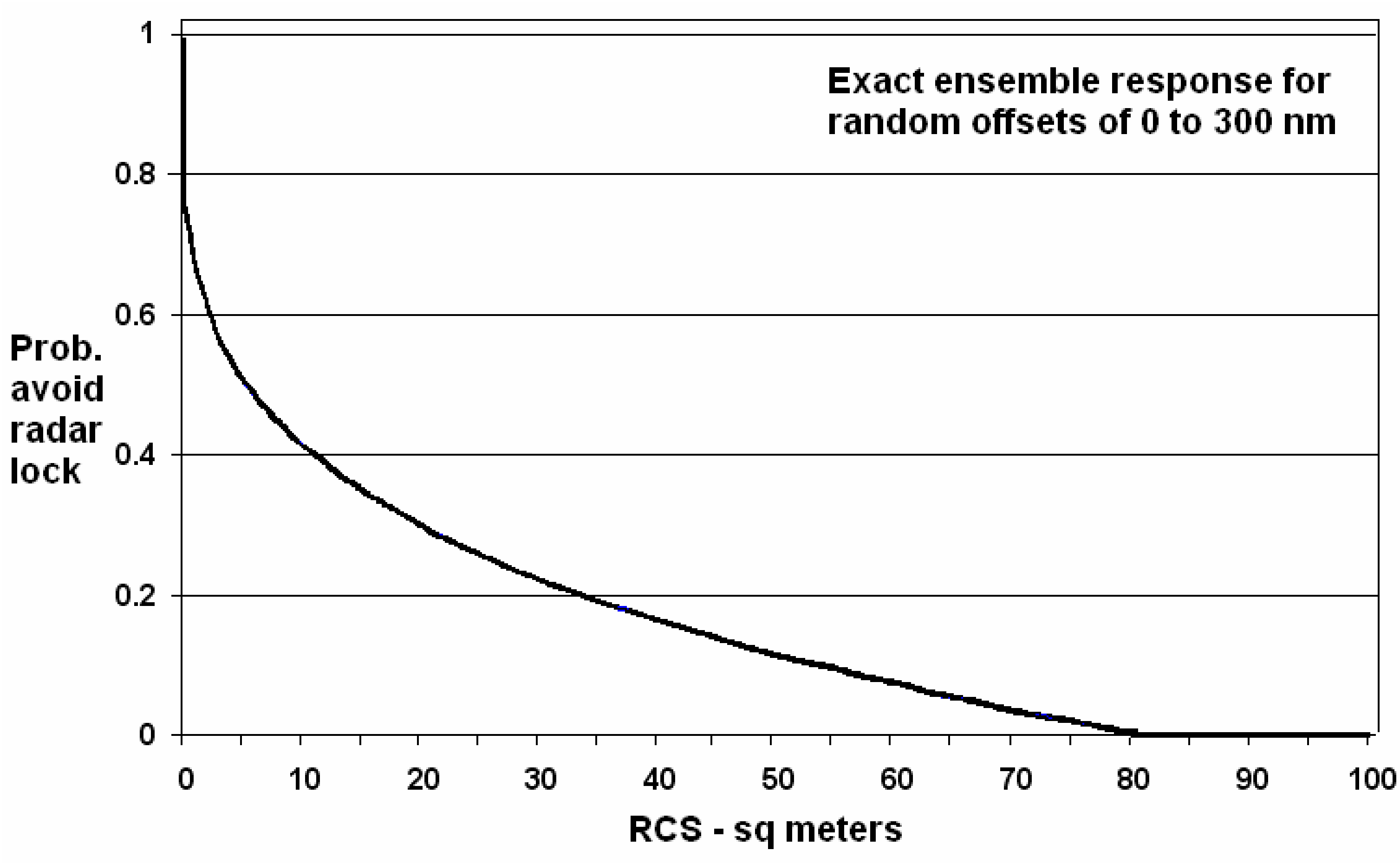
We could use many randomized offsets…

Equally-Weighted Results for 25 Random Offsets



For this simple problem, we can find the full ensemble.

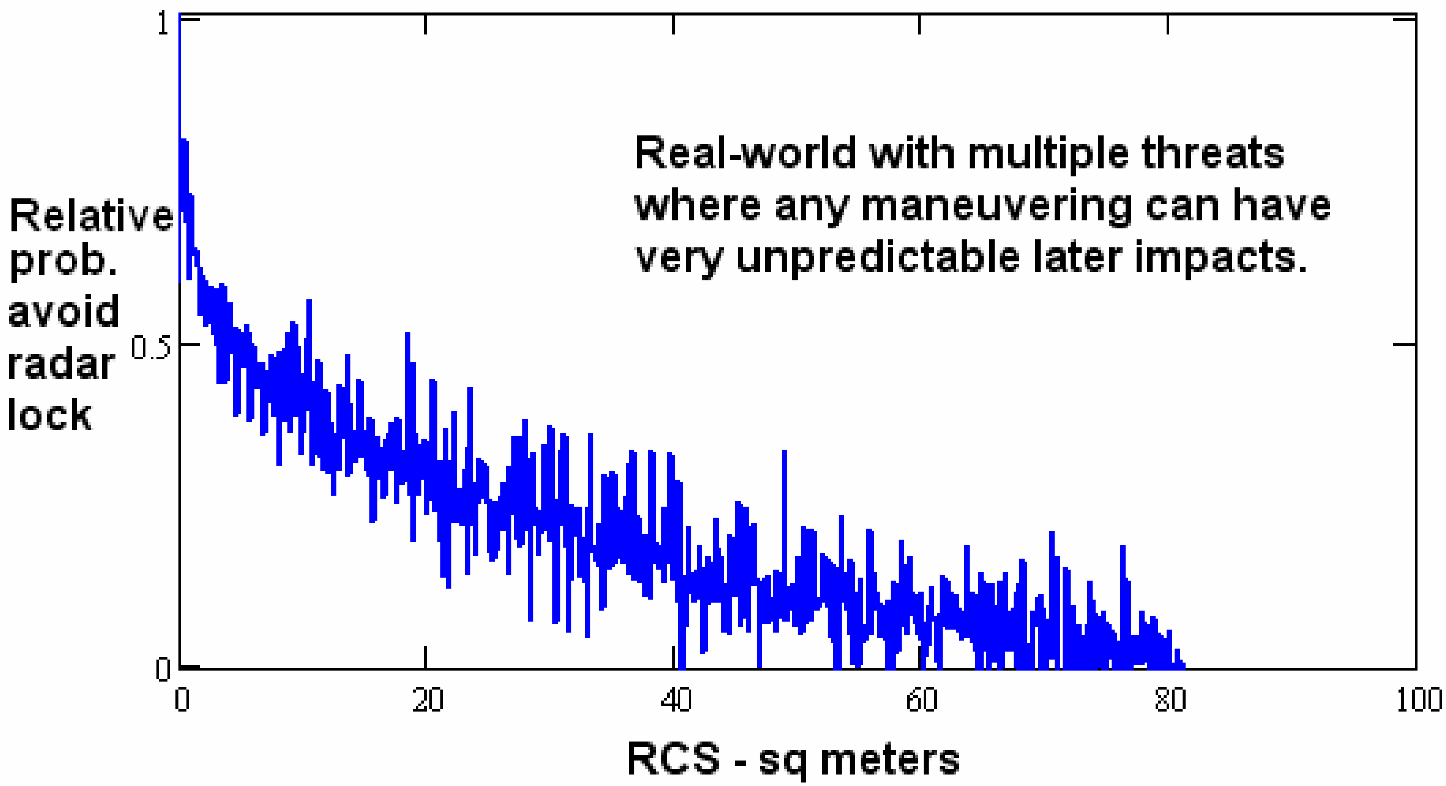
Representing the Ensemble of All Offsets



Full chaotic reality is not this nice

Chaotic Reality May Not Serve the Design-Trade Process

A “realistic” instantiation might give this result:

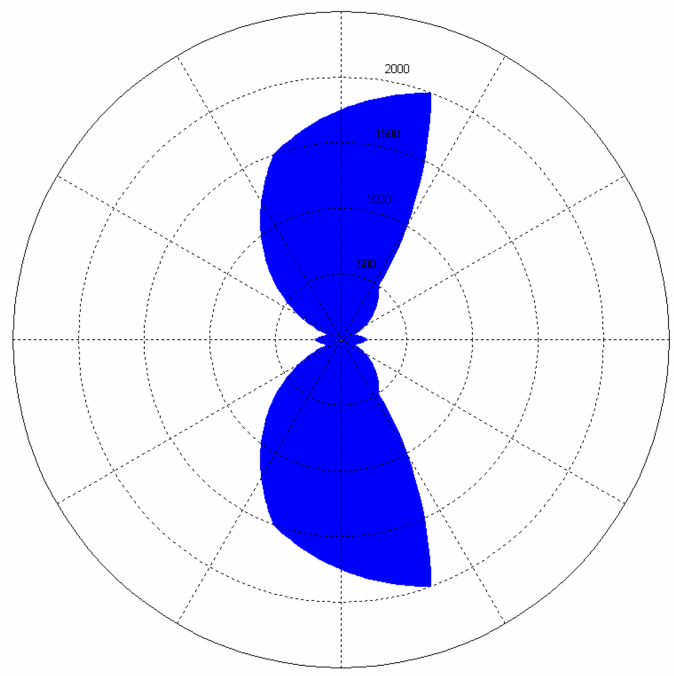


Can we obtain smooth ensemble responses for meaningfully complex problems?

Example: A More Complex SAM Encounter

We built BLINK, a proof-of-concept ensemble model sensitive to several aircraft and missile parameters:

- **Aspect-sensitive aircraft signature (radar range)**
- **Terrain masking (Line Of Sight)**
- **Intercept kinematics (A/C and missile mach, altitude, delays)**



The BLINK model examines these sensitivities.

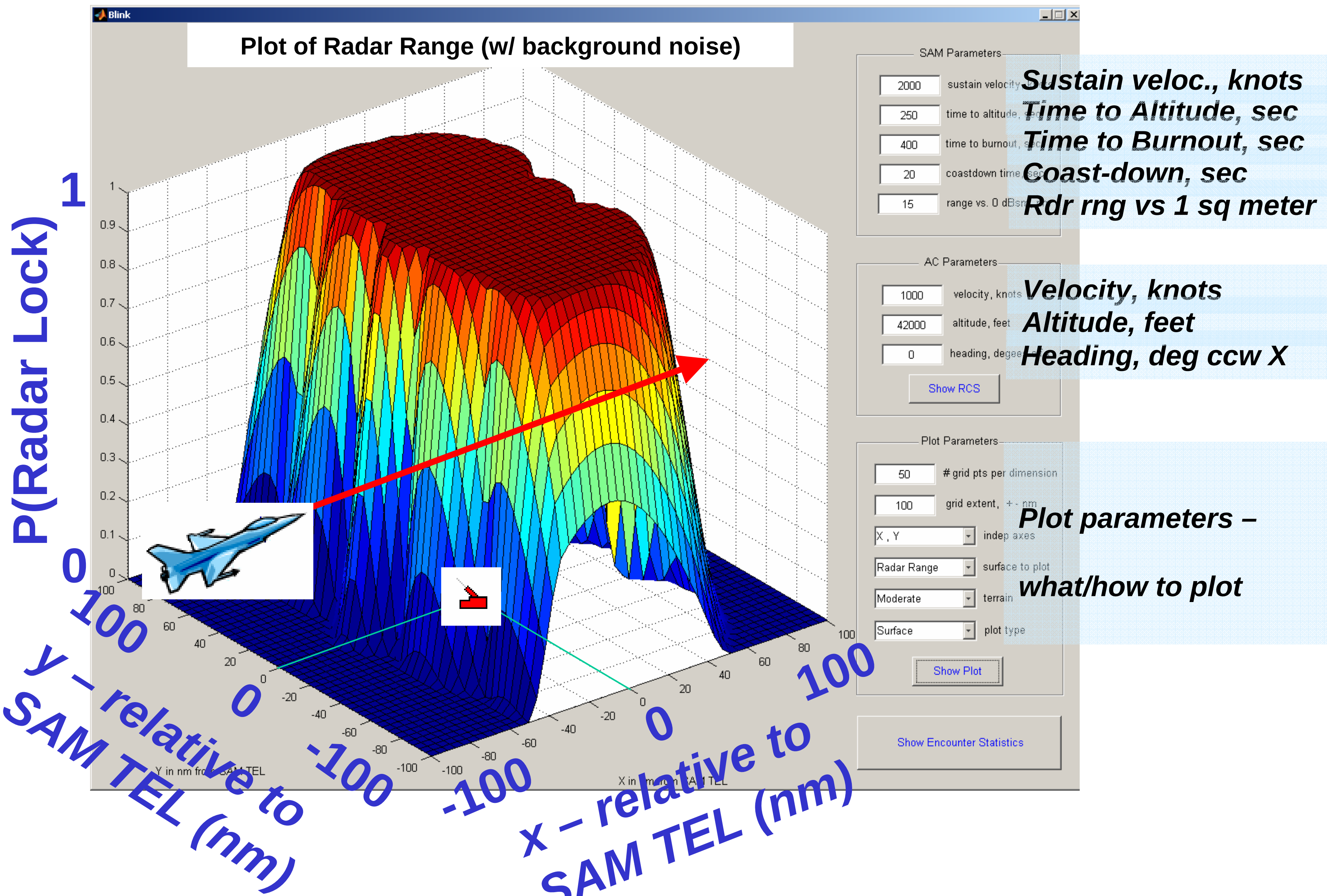
Radar Lock, LOS, and Kinematics Combine Via a Simple Serial System

All three factors must "work" for an intercept:
P(encr) = P(rdr range)*P(LOS)*P(kinematics)

Each factor in the combination requires a canonical form with the correct shape and asymptotical behavior – polynomials almost never provide suitable canonical forms.

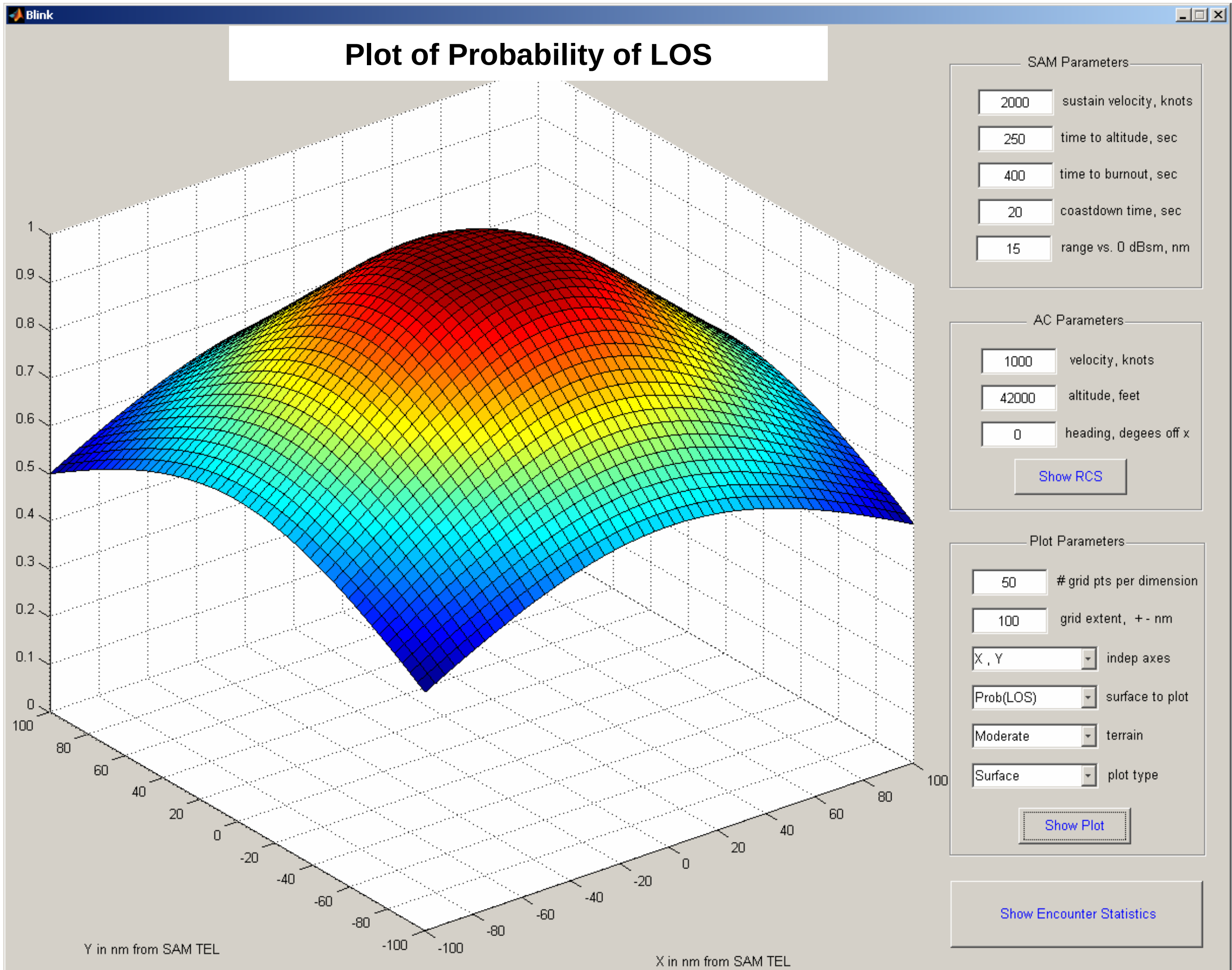
$\boxed{\textbf{Let's examine each component P( ).}}$

1. SAM Radar Range



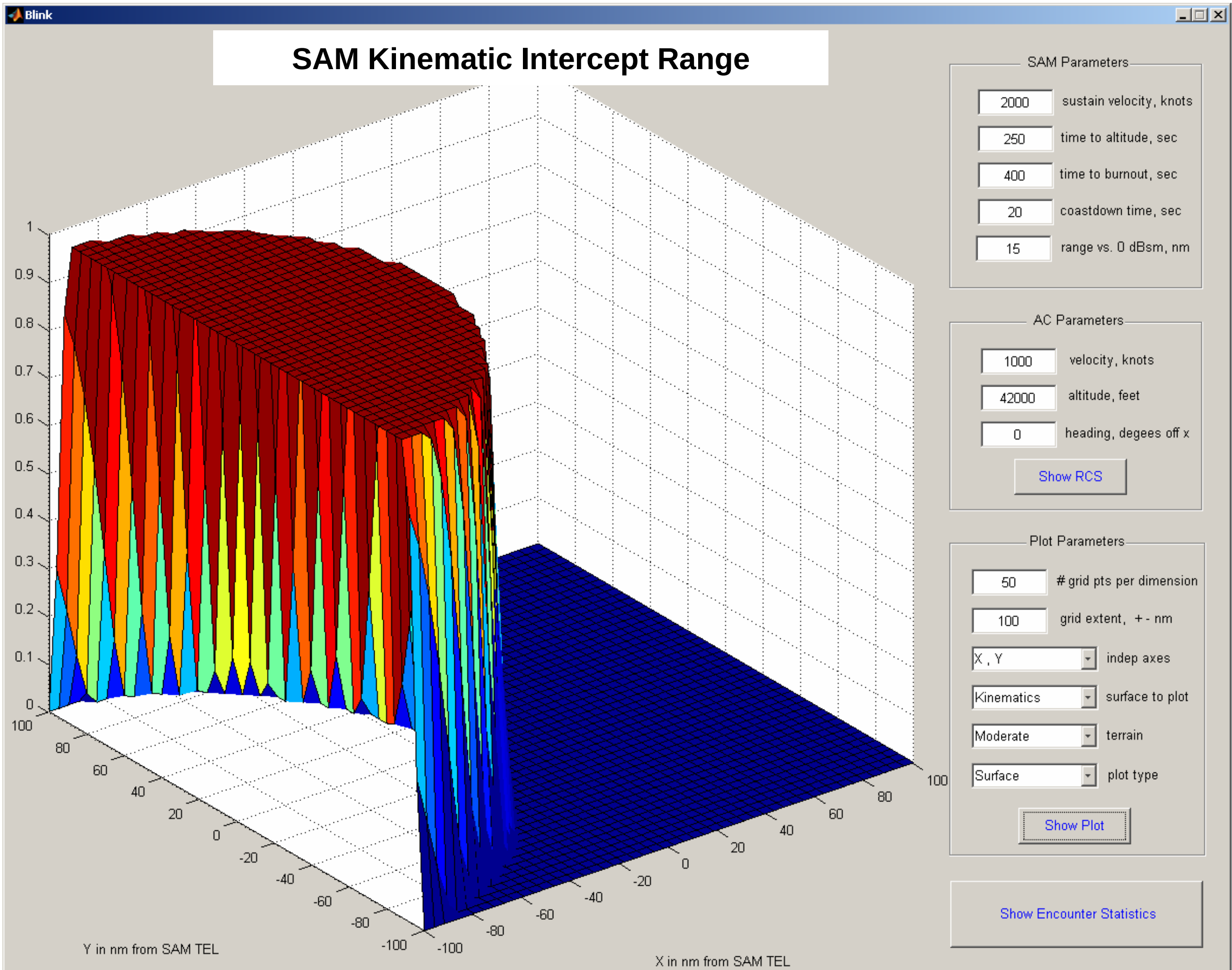
2. Line of Sight (LOS)

P(LOS)

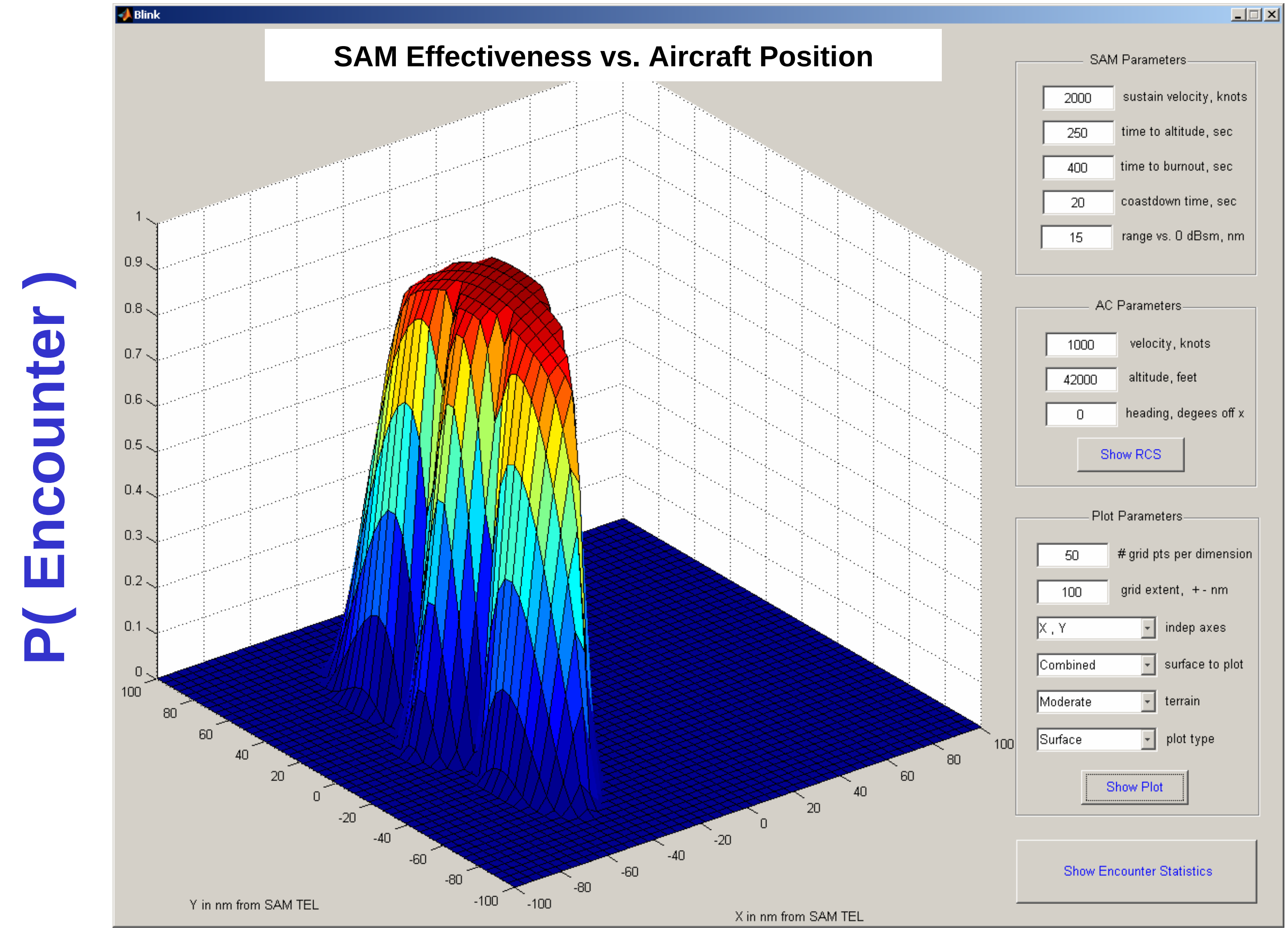


3. SAM Kinematic Range

P(SAM Kinematics)



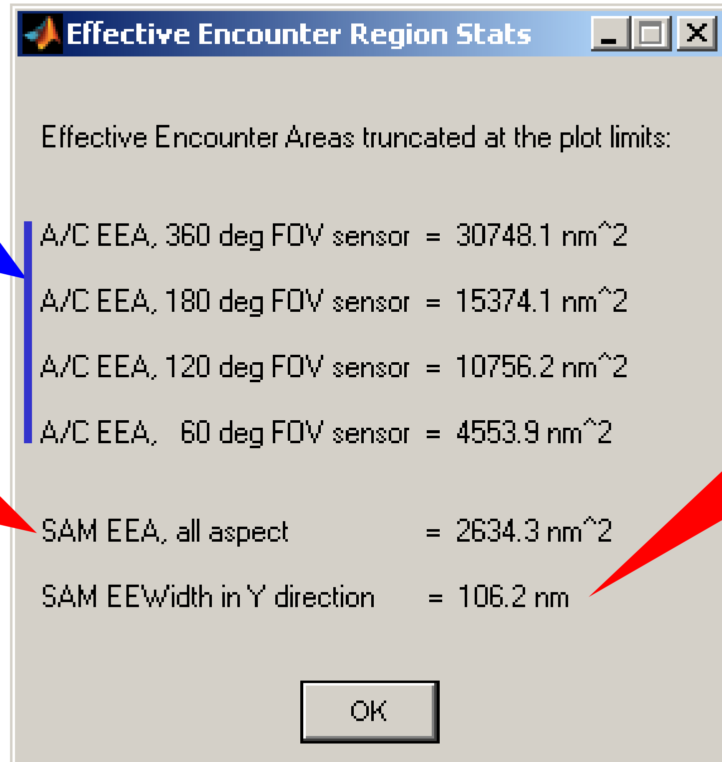
Combined Probability of Encounter



How can we use this ensemble?

BLINK Provides Encounter Areas and Widths

Determines detection rate of pop-up SAMs



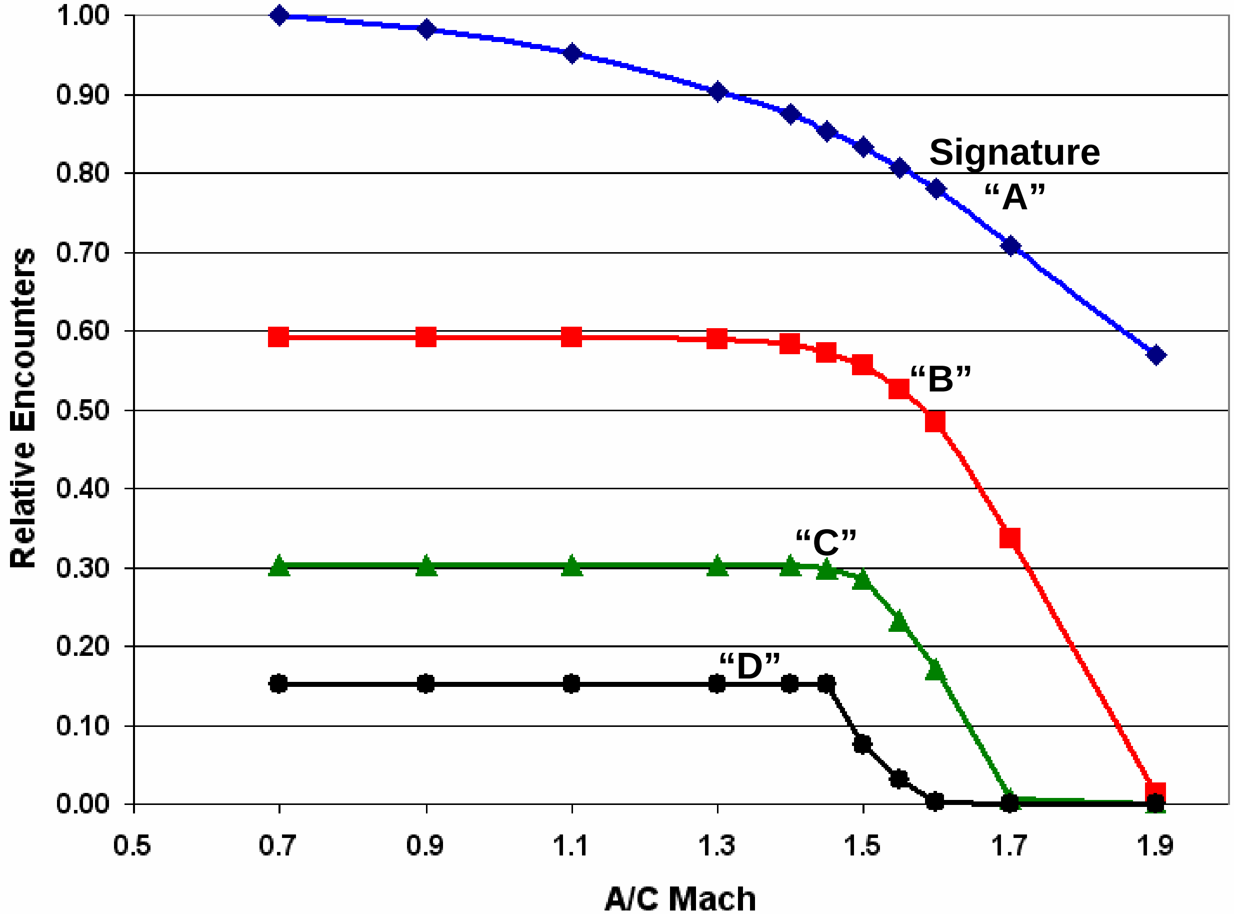
Determines opportunity rate by pop-up SAMs

Determines opportunity rate by cued SAMs

Given these areas and widths, a statistical mechanical methodology gives relative or absolute encounter rates

Example Results

Relative SAM Encounters vs. Mach and Signature



To be useful, we must be able to extend this approach

Possible Extensions of BLINK

- **Missile P(kill) by intercept aspect**
  - ***easy to incorporate as intercept aspect is known***
- ***3-D signatures***
  - ***not difficult given a flyout altitude-profile***
- **Kinematic-escape maneuvering**
  - ***easily feasible (but probably not closed form)***
- **Signature-management maneuvering**
  - ***probably only first-order effects***
- ***A/C* energy management per dogfight**
  - ***quite difficult***

How do ensemble models compare with instantiation?

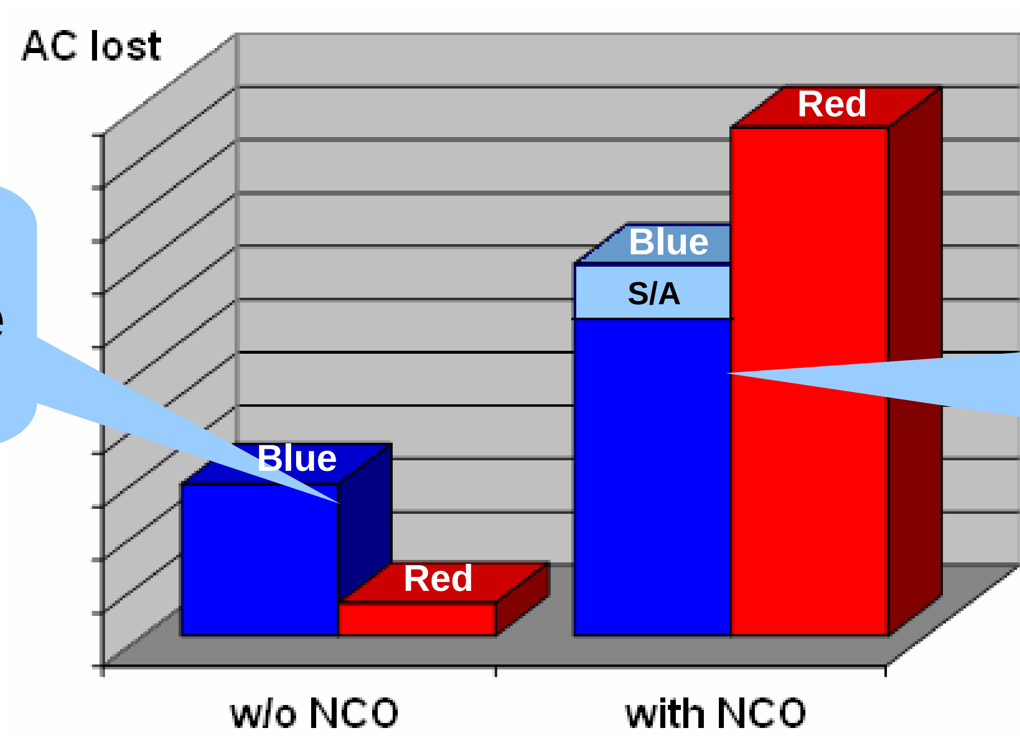
Approaches to Modeling Chaotic Systems

	Instantiation Model	Ensemble Model
Representation of probabilistic effects and input sensitivities	Models sampled values, that is, instantiations – "tail-number modeling." Objects in the model are typically physical entities: a SAM site, a strike A/C, ...	Models distributions, *not* specific realizations. Initial conditions are often distributions – some inputs and all results are ensembles that reflect distributions.
Advantages	Models capture extensive detail - "gets down in the weeds." Easy to visualize and to explain the model. "Presentation friendly."	Models generate an ensemble of outcomes by a distributional calculus such as Bayesian networks or influence diagrams.
Disadvantages	Can be difficult or impossible to ensure representative results.	Models cover only limited detail. Often hard to visualize or explain.
Mitigation of chaotic effects *within* the given MOPs, scenario and CONOPS	If non-deterministic, replications obtain the mean response *for the MOPs, scenario, and CONOPS*. Computational demands can be daunting.	Because the model treats the complete ensemble, not single instantiations, chaotic effects are intrinsically treated in the outcome distribution.
Mitigation of chaotic effects *resulting from* MOPs, scenario or CONOPS.	Chaos in the Scenario and CONOPS quite difficult to treat. Parametric studies are usually computationally constrained.	Chaos in the Scenario and the CONOPS is usually treatable by either an input distribution or by parametric studies.

But What About Our Opening Example?

A clue is supplied by a second MOM – Red losses.

LER
Red : Blue
0.24



LER
Red : Blue
1.4
(includes S/A)

The appearance of S/A losses was never explained

The Take-Home Message

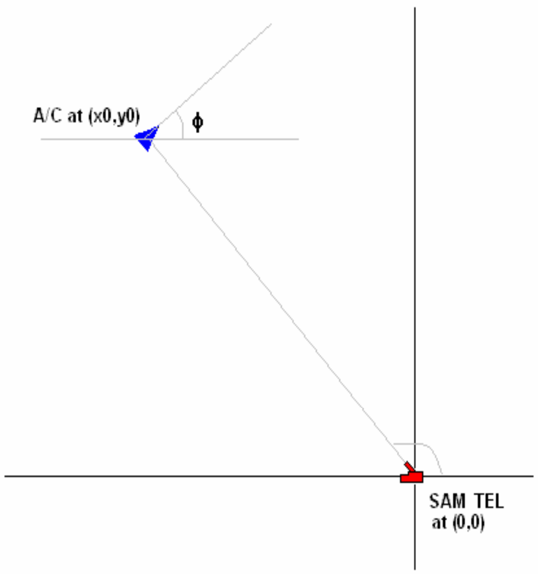
- **Instantiation models can have excellent resolution and fidelity**
- **But … hidden among the weeds can lurk undetected chaotic effects**

End of presentation –

backup slides follow

Kinematic Range is Based on Time To Intercept

Time to Intercept, T2i, Provides a Canonical Expression for Intercept Time/Location



We assume a non-maneuvering A/C, and perfectly predictive missile flight path, Our missile 3-D distance-flown approximation is $d = vm*(t - t0) \text{ for } t > t0$

This projects into an x,y distance-flown, $d = \sqrt{[vm\cdot(t - t0) + h]^2 - h^2}$ where we can think of t0 as "time to altitude". Our equations of motion are

aircraft: $x = x0 + v\cos(\phi)\, t \qquad y = y0 + v\sin(\phi)\, t$

missile: $xm = \cos(\alpha)^* \sqrt{[vm\cdot(t - t0) + h]^2 - h^2} \qquad ym = \sin(\alpha)^* \sqrt{[vm\cdot(t - t0) + h]^2 - h^2}$

Here v = A/C speed, vm = missile sustain speed, (x0,y0) = A/C location at t = 0, h = A/C altitude, t0 = "missile time to altitude", ϕ = A/C heading with a = sin(ϕ) and b = cos(ϕ), α = intercept heading.

If we find the intercept time, we can impute missile kinematic limits from an approximation of the missile coast down dynamics.

Solving the A/C and SAM equations of motion for time of intercept, T2i, we obtain:

$$T2i = \frac{y0\cdot v\cdot b + x0\cdot v\cdot a + vm^2\cdot t0 - vm\cdot h + \sqrt{2\cdot y0\cdot v^2\cdot b\cdot x0\cdot a + 2\cdot y0\cdot v\cdot b\cdot vm^2\cdot t0 - 2\cdot y0\cdot v\cdot b\cdot vm\cdot h + 2\cdot x0\cdot v\cdot a\cdot vm^2\cdot t0 - 2\cdot x0\cdot v\cdot a\cdot vm\cdot h + vm^2\cdot h^2 + v^2\cdot a^2\cdot vm^2\cdot t0^2 - 2\cdot v^2\cdot a^2\cdot vm\cdot t0\cdot h - v^2\cdot a^2\cdot y0^2 - v^2\cdot b^2\cdot x0^2 + v^2\cdot b^2\cdot vm^2\cdot t0^2 - 2\cdot v^2\cdot b^2\cdot vm\cdot t0\cdot h + vm^2\cdot x0^2 + vm^2\cdot y0^2}}{vm^2 - v^2}$$

One can do a similar analysis for an A/C attempting kinematic range evasion

Cautions

Ensemble models must stand on solid physics or statistics.

Otherwise they risk becoming "truthiness" models, yielding what Richard Feynman would call "Cargo-Cult Analysis."